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# Synchronisation of the EDML and EDC ice cores for the last 52 kyr by volcanic signature matching

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## Abstract

A common time scale for the EPICA ice cores from Dome C (EDC) and Dronning Maud Land (EDML) was established. Since EDML core was not drilled on a dome, the development of the *EDML1* time scale for the EPICA ice core drilled in Dronning Maud Land was carried on by creating a detailed stratigraphic link between this core and the one drilled at Dome C, dated by a simpler 1D ice-flow model. The synchronisation between the two ice cores was built via the identification of several common volcanic signatures. This paper describes the rigorous method, using the signature of volcanic sulfate, which was employed for the last 52 kyr of the record. By evaluating the ratio R of the apparent duration of temporal intervals between couples of isochrones, the depth comparison between the two cores was turned into an estimate of anomalies between the modelled EDC and EDML glaciological age models during the studied period. On average R ranges between 0.8 and 1.2 corresponding to an uncertainty within 20% in the estimate of the time duration in at least one of the two ice cores. Significant deviations of R up to 1.4–1.5 are observed between 18 and 28 kyr BP. At this step our approach is not able to unequivocally find out which of the models is affected by the errors, but assuming the thinning function at both sites and accumulation history at Dome C, which was drilled on a dome, as being correct, this anomaly can be ascribed to a complex spatial accumulation variability (which may be different at present day and in the past) and to upstream ice flow in the area of the EDML core.

## 1 Introduction

Ice cores drilled in polar areas represent natural archives of past environmental and climatic conditions on the Earth. Thus the glacio-physical and glacio-chemical stratigraphies can depict past atmospheric composition and climatic variability for time periods spanning up to several hundreds of millennia (Petit et al., 1999; NGRIP members, 2004; EPICA members, 2004) with time-resolutions higher than annual at some sites and for at least the whole of the Holocene (Vinther et al., 2006). The possibility to interpret such stratigraphies is closely related to the possibility to date the climate-linked events recorded in the ice. Absolute dating of the buried ice layers enables the comparison among records coming from different proxies (e.g. ice and sediment cores), in order to reconstruct a more complete and more reliable paleo-climatic scenario.

Due to the unavailability of any absolute (such as radiometric) dating method for old ice, ice core timescales are often based on glaciological models taking into account ice dynamics, thinning of the ice layers as they are buried in the glacier, and variation of the accumulation rate in different climatic conditions. Model parameters are then tuned by matching the ice-core record to selected well-dated events (Parrenin et al., 2007): e.g., climatic events recorded in dated marine records (Petit et al., 1999), large changes in cosmic ray flux (for example changes in Earth's magnetic field) recorded in $^{10}Be$ (Raisbeck et al., 2006), or volcanic events (Traufetter et al., 2004; Cole-Dai et al., 1997; Cole-Dai and Mosley-Thompson, 1999; Udisti et al, 2000; Castellano et al. 2005).

Despite these efforts, when comparing records from different sites, even on the same ice-sheet, age offsets always appear; the need to have a common age model at least for ice core stratigraphies from the inner part of Antarctica pushed the EPICA ice core community to produce the work presented in this issue. A first step toward the construction of a common age model for the ice-cores is the synchronisation between glacio-stratigraphies, i.e. the relative matching of profiles obtained from different drilling locations. Aside from absolute dating, searching for common events in different ice cores is of high value since the difficulty of dating the ice archives is strictly related to the characteristics of the drilling locations (e.g. dome location or upstream ice flow contribution, different accumulation rates). In the specific case of the EPICA project, the EDC ice core (75°06′S; 123°21′E, 3233 m a.s.l., Pacific/Indian sector) was drilled on a dome and was dated by an inverse method involving a 1-D glaciological model constrained and adjusted by a number of independent age markers (Parrenin et al., 2007). On the other hand, the EDML ice core (75°00′S, 00°04′ E. 2892 m a.s.l., Atlantic sector) was drilled in a site characterised by a not negligible contribution of up-stream ice that requires a complex 3-D age model (Huybrechts et al., 2007[1]). Therefore, the choice was made to transfer the EDC age model (EDC3) to the EDML stratigraphy in order to derive the EDML age scale (EDML1, Ruth et al., 2007). This implied a requirement to find as many isochronous signatures along the two cores as possible.

Volcanic signatures were extensively used in the past to match different ice core records; volcanic products (mainly ash, dust, tephra particles and $SO_2$, rapidly oxidised to $H_2SO_4$) are emitted into the high stratosphere and into the troposphere during volcanic eruptions, deposited on the Earth's surface via wet and/or dry deposition and preserved in ice or sediment stratigraphies as, respectively, tephra layers and sulphate (and in second order acidity and conductivity) spikes. The possibility to match ice-core records from different hemispheres by finding signatures of inter-hemispheric volcanic events (explosive tropical eruptions spreading products in both hemispheres through the stratosphere) is complicated by the presence of signatures of local to regional events recorded in just one ice sheet. On the other hand ice cores from the same ice sheet are presumed to record similar signatures (either global and regional), even if some local events of very low intensity can spread out their products, and therefore be recorded only at local scale; moreover, the total volcanic deposition can greatly differ in different locations depending on geographic location, atmospheric transport pathways and the ratio between wet and dry deposition contributions (Gao et al, 2006; Wolff et al., 2005).

Different methods can be used to identify volcanic signals with different degrees of specificity. Because it involves fast and non-destructive methods, the electrical conductivity of solid ice has often been used to identify or synchronise volcanic signature patterns: either the electrical conductivity method (ECM) (e.g. Clausen et al., 1997), or the dielectric profiling method (DEP) (e.g. Wolff et al., 1999) were used. Liquid

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conductivity can also be used when acidity is the main contributor to the ionic load. Although more time consuming to obtain, and generally at lower depth resolution, sulfate concentrations are a much more specific indicator for volcanic material (Udisti et al., 2004). For the comparison of EDC and EDML, all these methods were used independently by different investigators in order to ensure robust identification of common signatures (see Ruth et al., 2007). However, in the upper 52 kyr of the record, the comparison of continuous sulfate profiles from the two sites was considered the most robust and therefore the primary method for synchronization of the cores.

Sulphate stratigraphies were successfully used in the past to reconstruct paleovolcanic time series since they are not affected by post-depositional variations, except for very slow effects of diffusion in the deepest layers of ice cores (Barnes et al., 2003). High resolution profiles of sulphate on the two EPICA ice cores were produced by Fast Ion Chromatography (FIC, Traversi et al., 2002), with time resolution spanning from annual (in most part of the records) to multi-annual in the bottom sections. Such a temporal resolution allows the detection of volcanic signatures as sharp spikes, considering that stratospheric sulphate loads have a residence time of 2–3 years.

In this paper, we describe the synchronisation between EDML and EDC ice-cores via volcanic-matching using sulfate spanning the period from the present day back to 52 kyr BP as used during the procedure of construction of a common dating model for the EDC and the EDML ice cores (Parrenin et al., 2007; Ruth et al., 2007). The synchronisation was performed by mainly matching sulfate profiles in the two cores, supported by the independent matching of spikes in the solid and liquid electrical conductivity records (Wolff et al., 1999; Ruth et al., 2007). More than 200 isochronous volcanic events were identified by comparison of the high resolution sulphate profiles in the two cores.

## 2 Ice coring and processing

Drilling operations in Dome C began in 1996/97 and reached a depth of 788 m (where the drill got stuck). This core was named EDC96 and it spans about 45 kyr. The first 100 m of EDC96 were not suitable for chemical measurements and analysis was performed on a firn core named FIRETRACC, drilled a few hundreds of meters away. A new core was drilled from the surface starting in the 1999/2000 season (EDC99) and reached a depth of 3260 m (a few metres above the bedrock) in January 2005, covering a period of more than 800 kyr. The relative depths of identical features in the EDC96 and EDC99 cores has been determined using DEP (Barnes et al., 2006; Wolff et al., 2005); the shift in logged depth increases to about 1 m at 780 m depth, and the relative shift between the FIRETRACC, EDC96 and EDC99 cores has been taken into account (Udisti et al., 2004). EDML drilling operations started in 2000/2001 and were completed in January 2006, reaching liquid water at the bedrock interface at 2774 m depth. High resolution sulfate measurements have been performed on both the EPICA cores by FIC. Both cores have been completely processed and analysed, but sulphate data for the EDML core are at the moment available only for the first 1565 m (corresponding to about 52 kyr BP) while older ice is still under post-analysis processing. Sulfate records consist of a background level of mainly biogenic origin and sharp spikes of volcanic origin and allow the reconstruction of the paleo-volcanic records at the two sites with a depth resolution ranging from 0.8 cm (EDML, during Holocene) to 3.5 cm (EDC96). The temporal resolution of volcanic data in the last 50 kyrs is always better than 1 year for the EDML core and ranges from 1 to 3 years for the EDC core. The first 113 m of the EDML ice core (corresponding to the maximum depth in the drilling with a casing) have not been analysed for sulfate, so that the volcanic peak to peak comparison between EDML and EDC cores begins at this depth. For the first part of our match we used sulphate data at lower resolution from a firn core named B32, drilled about 2 km away from the deep drilling site during the pre-site survey (Traufetter et al., 2004).

### 2.1 Matching

The peak-to-peak comparison has been started from the surface of the shallow core B32 (sulphate data from Traufetter et al, 2004) and EDC96 as mentioned above. Figure 1 shows the very first part of the comparison, spanning from the present time back to 400 years BP. In the figure are also shown three known and well-dated volcanic events: the eruption of Krakatau (year of eruption 1884 A.D.), the double spikes of Tambora (1815 A.D.) and an unknown eruption 5–6 years earlier; the last volcanic signature shown in Fig. 1 is generally identified as Huaynaputina which erupted in 1600 A.D. These events and several of those found in the first part of the synchronisation are often used as temporal absolute horizons both in Antarctic and Greenland ice cores because of their global character (Langway et al., 1995 and Udisti et al., 2000), and have been used as age markers for the top part of the EDC3 model (Parrenin et al., 2007; Ruth et al., 2007). By using these signatures as common horizons, many other minor common signatures can be recognised, increasing the temporal resolution of the synchronisation. This procedure of matching major spikes and then recognising common minor signatures was used along all the ice core records.

Figure 2 shows the sulphate profiles for the B32, EDML and EDC96 cores after the volcanic synchronisation. By comparing the B32 sulphate profile with the EDML DEP profile along the first 113 m of the core, the depth to depth relationship between EDC96 and B32 has been transferred to the EDML core (Ruth et al., 2007). A depth off-set higher than 5 m is present already at this depth between the EDML and B32 cores. In this way a direct relationship between the two EPICA archives has been established up to the surface.

Figure 3 shows the synchronisation of the two cores in the time period between 6.2 and 7.6 kyr B.P. (corresponding to the depth interval 428.0–495.0 m of the EDML core and 208.0–244.0 of the EDC96 one). In the same plot the DEP profiles of EDC96 and EDC99 cores are also shown, as an example of the good link established among all the different records discussed here. In all records the background “noise” is low, due to the stability of the Holocene climatic conditions, and several volcanic spikes are easily detectable. Conversely, during the transition from LGM to the Holocene, a period characterised by significant accumulation changes as highlighted by the $\delta^{18}$O profile, only few common volcanic signals can be unambiguously identified (Fig. 4). Especially the EDC96 profile shows little variability even in periods where sulphate spikes in the EDML core are observed. The brittle ice characterising this section of the core could represent a drawback in finding common volcanic signals using sulfate, but also the continuous record achieved by using the DEP confirms that there is a genuine problem to find markers in this section. Luckily, three major eruptions (marked with $*$) are present at the very beginning of the transition and are well identified in both records. These three signatures represent a useful horizon for synchronisation in this section with very few common signals and were already used in the synchronisation between EDC and Vostok records (Udisti et al, 2004). They could represent a fundamental reference for the synchronisation of central Antarctica ice cores in the early deglaciation.

Figure 5 shows the peak to peak comparison between the two cores in the time range spanning from 45.6 to 52.6 kyr B.P. This section of the sulphate profiles shows a higher noise in both records due to the higher variability of the background concentrations in the glacial period (mostly due to accumulation changes rather than to variations in biological marine productivity – Wolff et al., 2006) and makes the comparison more difficult than in the Holocene. Vertical lines on the plot show the clearest volcanic matches all along this section. Over the long time period showed in Fig. 5, some non-linearities in the depth-to-depth relationship can be expected, due to the coupled effect of changes in the layer thinning and changes in the accumulation rates at one or both sites. Anyway, the availability of good records in different parameters allows a reliable synchronisation also in this section, as done by Udisti et al. (2004) in the EDC-Vostok volcanic matching.

In this section, as in other noisy ones, the detailed synchronisation was obtained by first identifying a few unambiguous major common signals in order to roughly tune the records, and then looking for minor events to fill in the sections between.

## 3 Depth to depth relationship

A total of 218 common volcanic events was recovered using the matching procedure described above. The depth-to-depth relationship between pairs of isochrones is shown in Fig. 6. Couples of common events pointed out using other parameters were also plotted on the depth-to-depth graph, showing a good consistency with the curve obtained with volcanoes. These other events consist of: an isochronous tephra layer at about 3.5 kyr BP (Narcisi et al., 2005; Kohno et al., 2005), well identified common dust features, and three features of the isotopic profiles (onset of Antarctic Cold Reversal, and of Antarctic Isotope Maxima 8 and 12 (EPICA community members, 2006). While the tephra layers (and on a slightly weaker basis, the dust features) must be synchronous, it is not self-evident that isotopic features must be synchronous at the two sites, and they are reported here just to highlight the consistency of our volcanic match.

The detailed synchronisation (see supplementary information) represents a useful tool to move from one core to the other and to synchronise at high detail different glaciological records and evaluate synchronicity, leads or lags of climatic and environmental events at the two sites.

Figure 7 shows an example of synchronisation of EDML $\delta^{18}$O and EDC $\delta$D low resolution profiles achieved using this procedure i.e. transferring EDML depth to EDC depth and then using the EDC3 timescale. The three arrows mark the three particular features used also in Fig. 6.

The curve obtained by plotting real depths of the events shows several changes of slope during the last 52 kyrs. It was not possible to satisfactorily fit the depth-to-depth relationship between the two cores with a simple polynomial function as done by Udisti et al. (2004) for the last 45 kyr for the Vostok and Dome C records. It is a proof that the glaciological dating at EDML is more complex than at Dome C or Vostok. This will be discussed in the following section.

## 3.1 Consistency of EDC and EDML glaciological dating models

Past ice flow has been modelled for both the EDML and EDC drilling sites, leading to so-called glaciological chronologies for these drillings. These models basically consist of two parts. First, the initial surface accumulation of snow is evaluated from the isotopic composition of the drilled ice (Jouzel and Merlivat, 1984). Second, the thinning function, i.e. the ratio of a layer to its initial thickness, is estimated with a mechanical flow model. The product of initial accumulation rate and thinning function is the annual layer thickness. The inverse of this quantity, i.e. the number of annual layers per meter, is then integrated from the surface to a certain depth to obtain the corresponding age at this depth.

For the EDC ice core, which is located on a dome position, horizontal flow velocity is assumed to have been always negligible, and bottom ice is assumed to originate from the current drilling site, so that a simple one dimensional model can be used for the modelling of the age scale (Parrenin et al., 2007). The EDML ice core was drilled on a gentle sloping ridge with small but not negligible horizontal flow velocity (about 1m/yr) (EPICA community members, 2006). For this reason, deeper ice at Kohnen Station originates from upstream positions at higher altitudes and does not represent the deposition at the current drill site. By the use of a nested 3D flow model (Huybrechts, 2002; Pattyn, 2003) it was possible to evaluate the thinning function as well as the spatial origin of the drilled ice (Huybrechts et al., 2007[1]).

The volcanic match between EDC and EDML can be used as a test of the consistency of the glaciological dating models. Indeed, this consistency can be estimated by plotting the ratio R of the duration of the intervals between two consecutive volcanic markers in the modelled EDML and the EDC3 tuned-glaciological age scale (Fig. 8 bottom panel). If R equals 1 in a certain time period, that means the duration between two isochrones is the same in both cores for the modelled age scale (obviously in the final synchronised age scales, R would always be 1). This would be the case in particular, if all modelling steps were correct (i.e. accumulation and thinning at both EDC and

EDML). In periods where R is greater than 1 the duration estimate is larger at EDML than at EDC and vice-versa.

The bottom panel in Fig. 8 shows deviations from the theoretical value of 1.0 during the last 52 kyr: R for the whole studied range has a standard deviation around 1.0 of 0.18. From these results, we can deduce that the confidence interval of the duration between couples of synchronous events in at least one of the two cores is not better than about 20%, if glaciological models are used. Our volcanic matching thus proves itself to be a useful tool to evaluate the average error in glaciological age scales. This ratio is consistent with the standard ratio 0.8 obtained by Parrenin et al., 2007 between EDC and Dome F by isotopic matching of the two ice cores. It should be noted that in this later case, the time interval between synchronisation tie points is larger in average and that the total synchronisation period is larger (300 kyr) as well.

Figure 8 shows that from 0 to 12 kyr BP, R slowly decreases from 1.2 to 0.8 and then it suddenly increases up to around 1.2 and remains roughly constant back to ~22 kyr. The maximum value of R is obtained at around 24–26 kyr, where the disagreement between EDML and EDC exceeds a factor 1.4. Finally, between 28 and 50 kyr BP, R shows small oscillations between 0.8 and 1.2.

The differences pointed out by volcanic matching cannot be unequivocally ascribed to any of the four modelled parameters and we can only move on by assumptions. First, the thinning models for the two cores are supposed to be correct in the relatively young top section, where the thinning functions are quite smooth and close to linear because the total ice thickness around the drilling sites is roughly constant. Moreover, at Dome C, the glaciological settings allows for an easier modelling leading to a confident estimate of the accumulation history (Parrenin et al., 2007). This is further supported by the fact that the depth-depth relationship between EDC and Vostok (Udisti et al., 2004) is more regular than between EDC and EDML (Fig. 6). At EDML, the initial surface accumulation rate may not be simply related to the isotopic content of the ice because of several reasons: 1) different glaciological settings upstream of the drilling site (higher surface elevation, possibly different origins of the precipitations, etc.). 2) Post deposi-



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tional surface snow redistribution by wind depending on surface undulations, which is, in particular, a consequence of the ice flow above bedrock reliefs.

As a consequence, we assumed here that most of the inconsistencies between the age models come from spatial and temporal variations not accounted for in the modelling of accumulation history at EDML. We therefore deduced a so-called stratigraphic accumulation rate at EDML by multiplying the model based accumulation rates at EDML by the ratio R (see Fig. 8). This new accumulation rate at EDML, associated with the thinning function, produces an age scale which is consistent with the EDC glaciological one. Figure 8 (top panel) shows the comparison between our stratigraphic accumulation rate and those derived by thermodynamical reasoning from the stable isotopes content. Overall the glacial/interglacial accumulation amplitude determined by both methods agrees very well. The deviation of the accumulation rates derived by both methods is generally smaller than 20%. Given that these methods are virtually independent this is good proof of the applicability of the thermodynamic relationship of water vapour saturation pressure to derive past accumulation rates that can be regarded as largely representative for high resolution reconstruction of e.g fluxes of aerosol deposition (Wolff et al., 2006). When comparing the accumulation records in more detail certain systematic differences appear. The stratigraphic accumulation is significantly higher than the thermodynamic one for two notable time periods: during the Antarctic Cold Reversal (ACR) and during the period following AIM3. Conversely, the stratigraphic accumulation is lower than the thermodynamic one during the early Holocene and during AIMs 3–4, and AIMs 11–12.

We clearly see in both the accumulation profiles the maxima corresponding to AIM 8 and 12, and to the ACR. A maximum is also found at around 25 kyr, corresponding to the period where the ratio R shows its highest value. This maximum of the stratigraphic accumulation rate is especially surprising because at the LGM (about 20 kyr BP) accumulation rates derived by both methods agree perfectly and R is very close to 1. We should also remark that the temperature change (as derived from $\delta^{18}$O values) in the time interval 28 000 to 18 000 yr BP is minimal and therefore no strong accumulation rate changes are expected during that interval. A possible explanation for this anomaly is a spatial variation of accumulation upstream of the EDML drilling site in the past which is different and more pronounced than one for recent conditions as derived from isochronous layers in shallow radar profiles (Huybrechts et al., 2007[1]). Because only the recent spatial accumulation variability can be taken into account in the flow model at EDML, a change in this variability in the past will lead to excursions in R.

It is important to stress that this conclusion is drawn by taking the assumption above described at face value, but we cannot completely rule out the effect of sources of uncertainties that were not taken into account in the EDC ice flow model such as that ice is not an isotropic material and that the dome position moves with time. Similarly, errors may be present in the EDML thinning evaluation.

## 4 Conclusions

A tight link among more than 200 volcanic isochrones along the last 52 kyr of the EDC and EDML ice cores has been established and applied to synchronise these two ice cores on a common time scale allowing the construction of the EDML1 timescale, in spite of the complex glaciological settings of the EDML area. This volcanic synchronisation was also used to bring to light inconsistencies among modelling of past accumulation rates and thinning at the two drilling sites. Indeed, the ratio $\Delta age_{EDML}/\Delta age_{EDC}$ (R) from the glaciological model age scales has been used as a tool to point out the sections where at least one model fails significantly. We estimate that the mean ratio in the durations of climatic events in both cores for the last 52 kyr is 1.0, with deviations from this value of the order of 20%, which gives an estimate of the confidence interval of the glaciological time scales. The maximum value of R is 1.4–1.5 which is found at ~25 kyr BP, where we suggest EDML accumulation may be anomalous even if it is not clear yet what is the origin of this anomaly.

Since we can not solve the question which of the two age models is responsible of the discrepancies between the two glaciological models (and we can not exclude that both models are responsible for considerable uncertainties) we made the assumptions that the model of thinning functions at both sites (at least at these relatively low depths), as well as the past accumulation rates at Dome C are correct. This was originally also the reason why for the EDML ice core the age scale was directly derived from the EDC3 time scale via our volcanic stratigraphic link. Using our stratigraphic match, we deduced a so-called stratigraphic accumulation for the EDML ice core. The comparison between this accumulation and the thermodynamical one proved an overall agreement during the last 52 kyr proving that the accumulation rates derived from the isotopic content can be confidently used for flux calculations of ice impurities. The large anomaly between the two accumulation reconstructions at ~25 kyr remain still unexplained and only new studies of the variations of the accumulation upstream of the drilling sites may help of understanding the processes involved.

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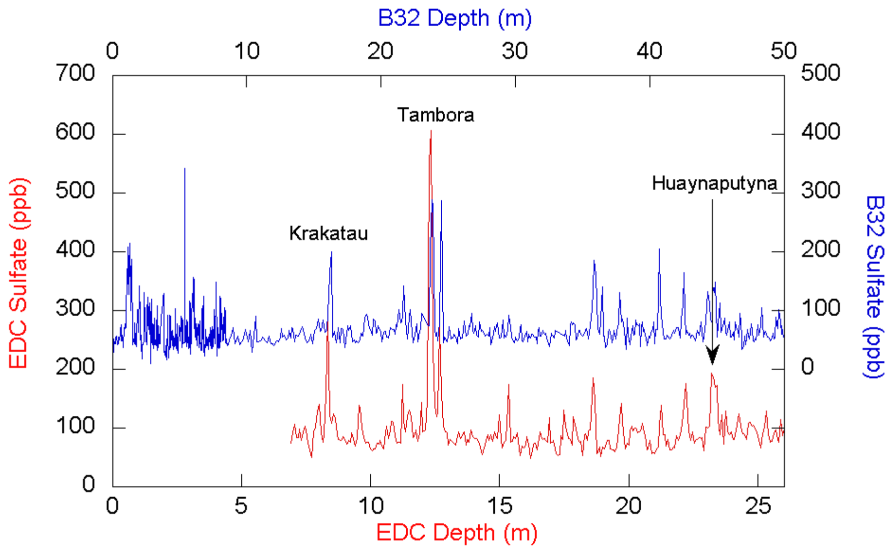


**Fig. 1.** Sulfate profiles of the top parts of the EDC and B32 ice cores spanning the last 400 years of volcanic history recorded in Antarctic ice. Three known and well-dated volcanic events are pointed out: Krakatau (1884), Tambora (1815 A.D.) and Huaynaputyna (1600 A.D.)

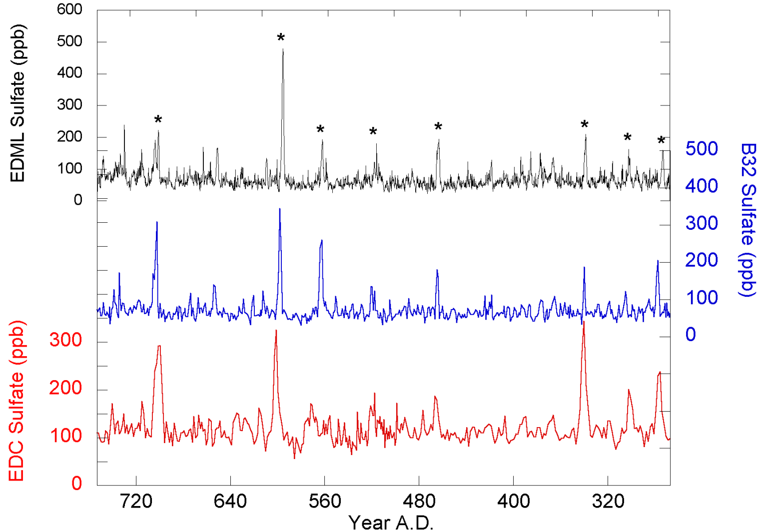


**Fig. 2.** Sulphate profiles relative to EDC96, B32 and EDML sulfate records plotted on a common age scale after the volcanic synchronisation. The corresponding depth ranges for the three cores are: 58.3–76.0 m (EDC), 114.0–148.7 m (EDML) and 109.7–143.7 m (B32). Events marked with (*) have been used to build the stratigraphic link between the EDC and the EDML cores.

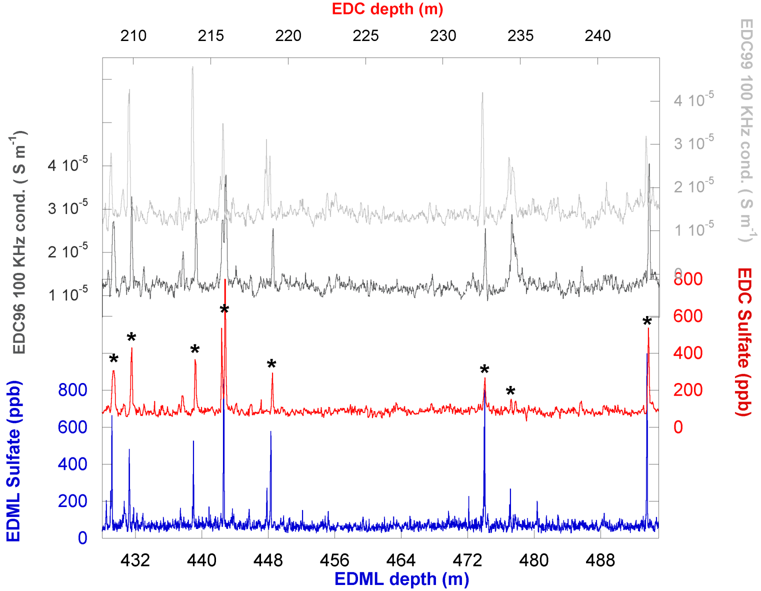


**Fig. 3.** Synchronisation of the EDML and EDC cores in the time period between 6.2 and 7.6 kyr B.P. (corresponding to the depth interval 428.0–495.0 m of the EDML core and 208.0–244.0 of the Dome C one). Both records show a low background "noise" and several common volcanic spikes are clearly visible. The DEP profiles of EDC96 and EDC99 in the same depth range are also shown in order to point out the link established between different kind of records. Events marked with (*) have been used to build the stratigraphic link between the EDC and the EDML cores.

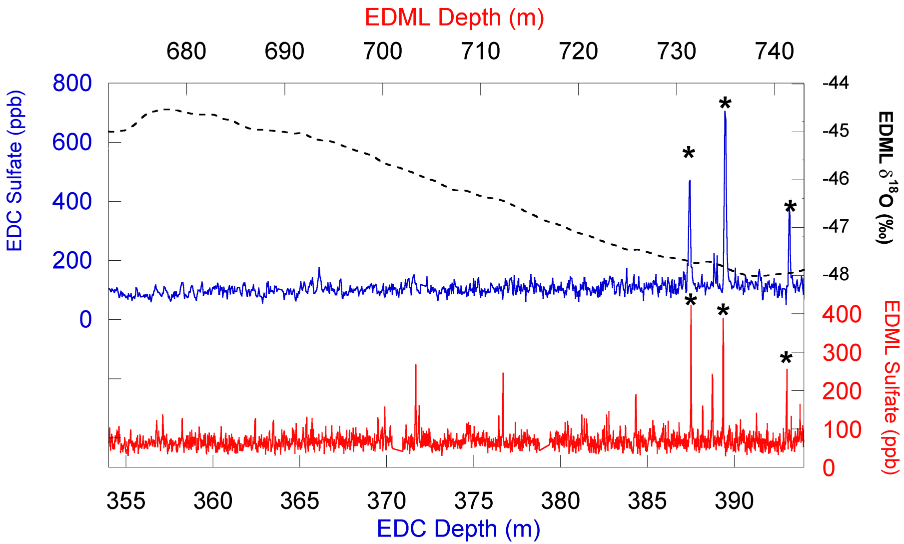


**Fig. 4.** Synchronised sulfate profiles of the two EPICA records during the transition from LGM to the Holocene. Few common volcanic signals are detected. Three major eruptions (marked with $*$) are shown at the very beginning of the transition and they represent a useful horizon for the synchronisation in this section. The EDMLg$\delta^{18}$O smoothed profile (black dashed line) is also shown in order to highlight the significant accumulation change in this part of the comparison (from 13.1 to 11.4 kyr BP).

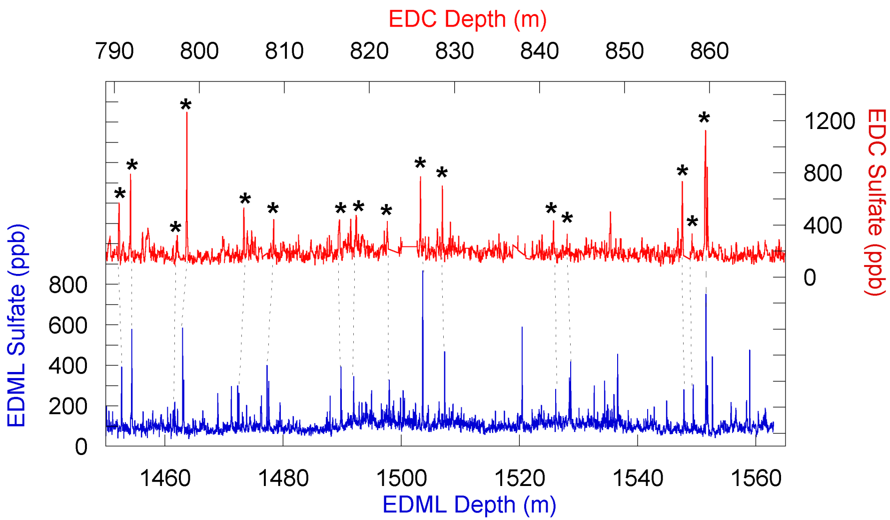


**Fig. 5.** The last part of the volcanic synchronisation is shown, covering the time range between 45.7 and 52.5 kyr BP. An higher background noise with respect to the Holocene is visible, but several common signals are easily detectable (marked with *) and were used for the synchronisation of the two EPICA cores.

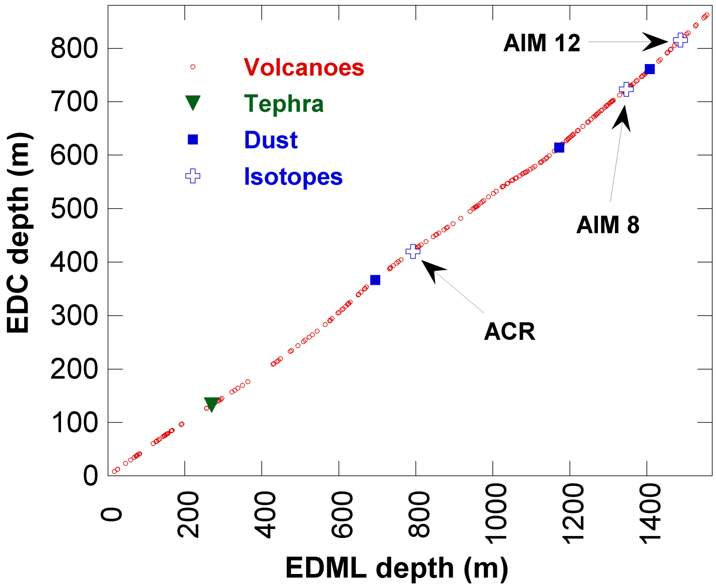


**Fig. 6.** Depth-to-depth relationship of the common volcanic events detected in the two ice cores. Couples of synchronous events pointed out using other parameters (isotopes, dust and a tephra layer) were also plotted on the graph.



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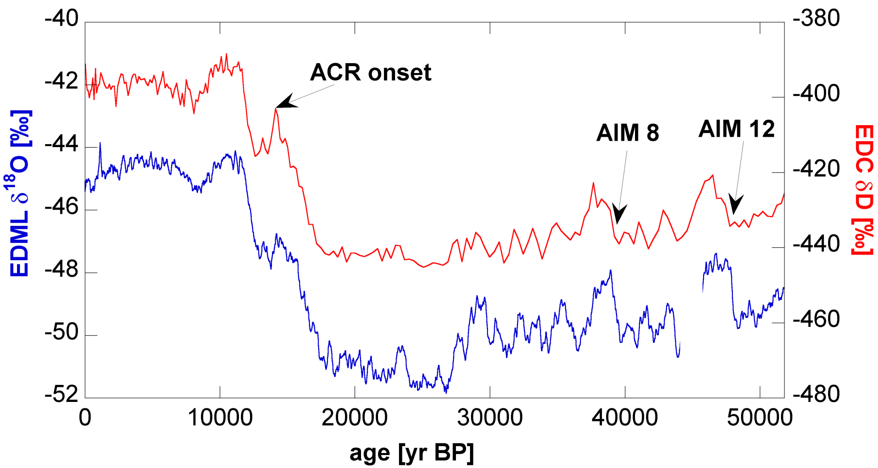


**Fig. 7.** Synchronisation of EDML $\delta^{18}$O and EDC $\delta$D low resolution profiles achieved using the common volcanic signatures. The three arrows mark the three peculiar features used also in Fig. 6.

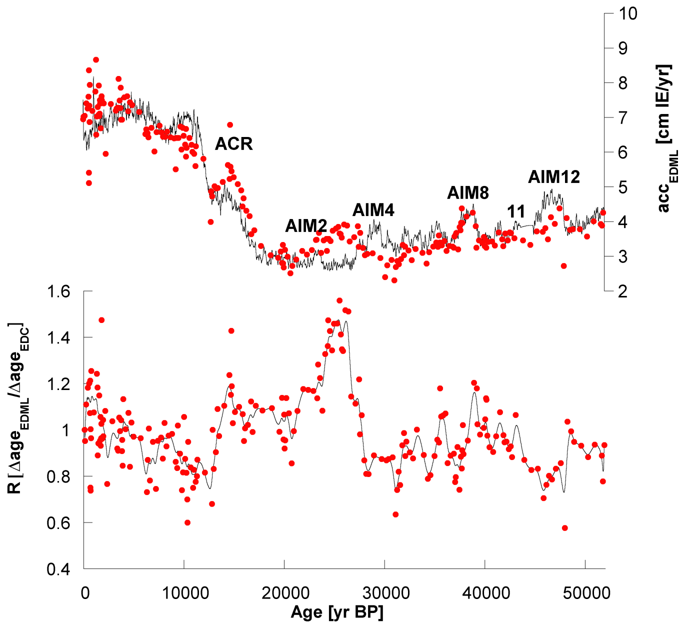


**Fig. 8.** Accumulation reconstructions for the EDML ice cores. Stratigraphic (red dots) and pure thermodynamic (grey dotted line in 100 yr resolution) accumulation rates are shown in the top panel. The bottom panel shows the $\Delta age_{EDML}/\Delta age_{EDC}$ ratio (R) between couples of volcanic events dated using EDC3 and the EDML glaciological model (red dots and smoothed line).



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